Simulations of Relativistic Jet Formation In Radio Sources

David L. Meier

Jet Propulsion Laboratory

Oxford Meeting

On Particles & Fields in Radio Galaxies

3-5 August, 2000

Talk Outline

- Introduction: observed Lorentz factors
- Review of steady state simulations
- Pseudo-relativistic simulations and the "magnetic switch"
- General relativistic jet production and rotating black holes
- Possible scenarios for Active Galactic Nuclei

Acknowledgements

- Collaborators
  - <u>General Relativistic simulations</u>: S. Koide (Toyama University), K. Shibata, T. Kudoh (National Astron. Obs, Japan)
  - <u>Pseudo-relativistic simulations</u>: D. Payne (Intel), K. Lind (Silicon Graphics), S. Edgington (Caltech), P. Godon (Space Telescope)

Observed Lorentz Factors

- Component proper motions: $\Gamma \equiv (1 - v^2/c^2)^{-1/2} = 5\text{-}10$
  (NOTE: this may measure a pattern speed only)

- Brightness temperature measurements of Doppler boosting:

$$\Gamma \geq 0.5\ T_{B,\mathrm{measured}} / T_{B,\ \mathrm{rest\ frame}}$$

  – $T_{B,\ \mathrm{rest\ frame}} \approx 10^{11}$ K for an equipartition synchrotron plasma

  – Some measured brightness temperatures and inferred Lorentz factors:
    - Ground Radio VLBI: $T_{B,\mathrm{measured}} \geq 10^{12}$ K $\Rightarrow \Gamma \geq 5$
    - Space VLBI (VSOP): $T_{B,\mathrm{measured}} \geq 7 \times 10^{12}$ K $\Rightarrow \Gamma \geq 35$
    - Intra-day variable sources: $T_{B,\mathrm{estimated}} \sim 5 \times 10^{14}$ K (?) $\Rightarrow \Gamma \geq 2500$ (?)

The Case for Space VLBI (Part I)

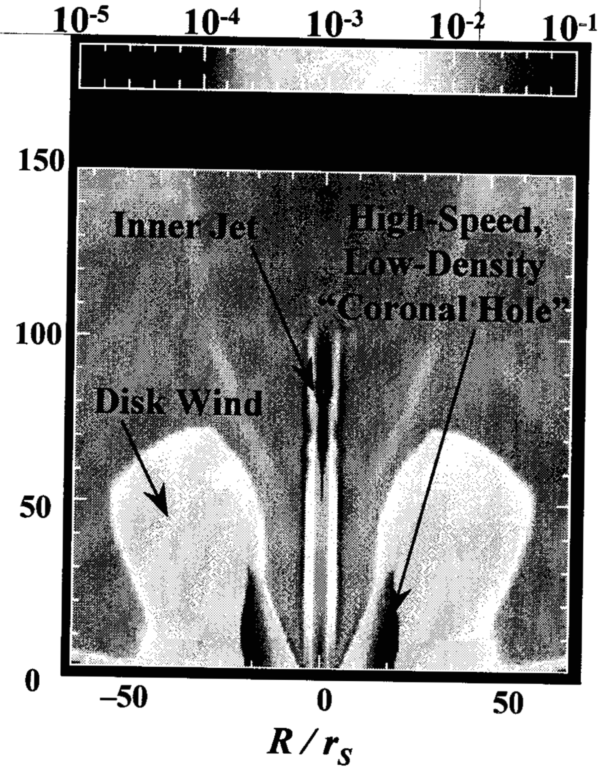
- Measuring brightness temperatures is the best (and possibly only) method for determining the highest velocities nature can achieve
- A measured brightness temperature depends only on the source flux and the length of the baseline
- T_B measured from the ground is limited to $< 10^{12}$ K, regardless of observing frequency
- Higher T_B, and Lorentz factors significantly above 10, can be measured only with baselines much longer than an earth diameter ⇒ NEED SPACE VLBI

- VSOP has found unresolved, ~1 Jy, high T_B cores in nearly all sources studied (see Lister *et al.*, Piner *et al.* this meeting)

⇒ A HIGHLY SENSITIVE SPACE VLBI MISSION WITH LONG BASELINES (*e.g.*, ARISE-LITE, VSOP-2) IS CRUCIAL FOR RESOLVING THESE CORES AND MEASURING THEIR ACTUAL JET SPEEDS

Conclusions

- The magnetically-driven outflow has two main components:
  - A slowly-collimating wind from the surface of the accretion disk
  - A highly-collimated jet from the inner edge of the disk or torus



- Both types of outflow are subject to "magnetic switching":
  There exists a critical MHD power $L_{crit} \equiv E_{escape}/\tau_{free\text{-}fall}$ (analogous to the Eddington limit) such that
  - When the MHD power in the rotating magnetic field $L_{MHD} < L_{crit}$, gravity is ***im**portant*, and the jet/wind speed is limited to $V_{jet} \sim V_{escape}$
  - When $L_{MHD} > L_{crit}$, gravity is ***un**important*, and the jet/wind speed is determined mainly by the output MHD power and the mass loss:

    Non-relativistic: [redacted] $V_{jet}^2 \sim L_{MHD}$

    Relativistic: Γ_{jet} [redacted] $c^2 \sim L_{MHD}$

- High MHD power + low mass loss (Poynting-flux-dominated)

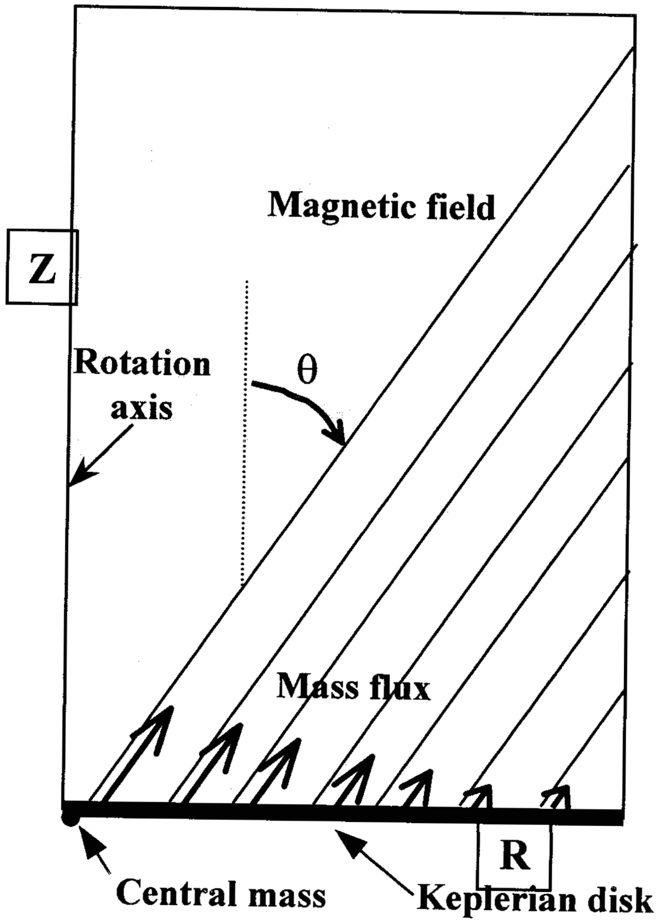
  $\Rightarrow$ high Lorentz factors

Conclusions (continued)

- When the accreting object is a <u>rotating</u> black hole:
  - The jet is accelerated from the "frame-dragged" accreting matter inside the ergosphere
  - Recall:
    - The horizon is much smaller than one Schwarzschild radius (GM/c^2 for maximal Kerr)
    - All matter in the region $R < 2\ GM/c^2$ (the "ergosphere") must rotate with the black hole
  - The strongest and fastest jets occur when:
    - The black hole is rotating rapidly
    - The accreting material plunges rapidly into the ergosphere
      - ***E.g.*, when the accretion is an Advection-Dominated Accretion Flow [ADAF] or**
      - ***E.g.*, when the accretion disk counter-rotates relative to the black hole**

Review of Steady State Simulations

- Some numerical simulations have attempted to reproduce the steady state Blandford & Payne solutions (Ustyugova et al. 1995, 1999; Ouyed et al. 1997; Krasnopolsky et al. 1999)
- Key ingredients in steady-state simulations:
  - An infinitely-thin accretion disk boundary condition, stretching to R=0
  - A central mass gravitational potential with a small "smoothing radius"
  - Keplerian rotation
  - Fixed vertical magnetic field B_Z
  - Fixed mass flux along the field lines
  - Important: the following quantities on the boundary are allowed to adjust to the steady-state solution: radial B_R and toroidal B_φ magnetic field strength, and radial velocity V_R

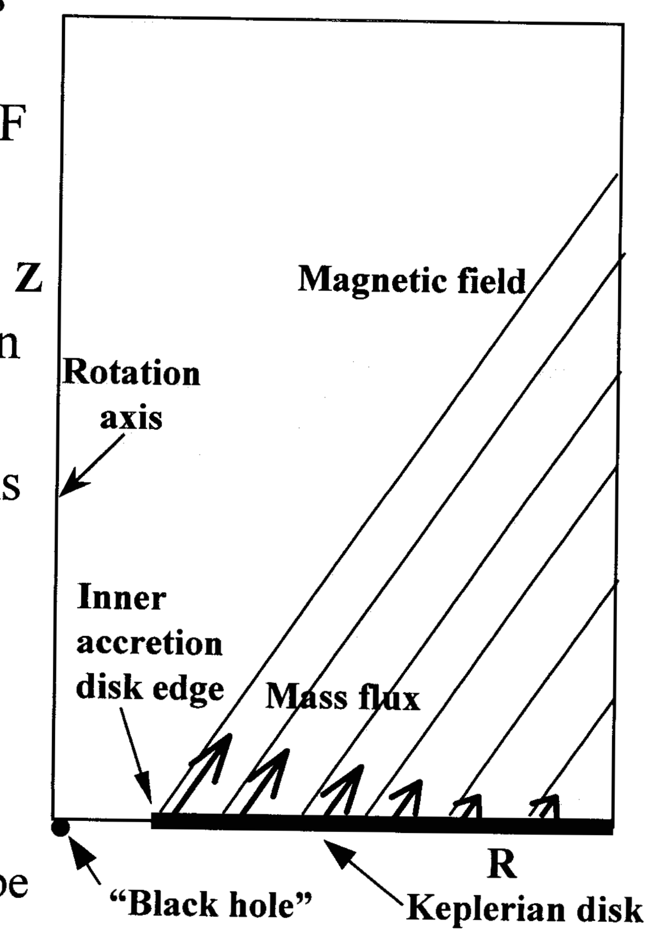


Pseudo-Relativistic Simulations of Black Hole Accretion Disks

- When the disk coronal material is not a relativistic gas ($c_{sound} < c$; $V_{Alfvén} < c$), the non-relativistic MHD equations are nearly identical to the relativistic ones, IF we replace the velocity V with the proper velocity U

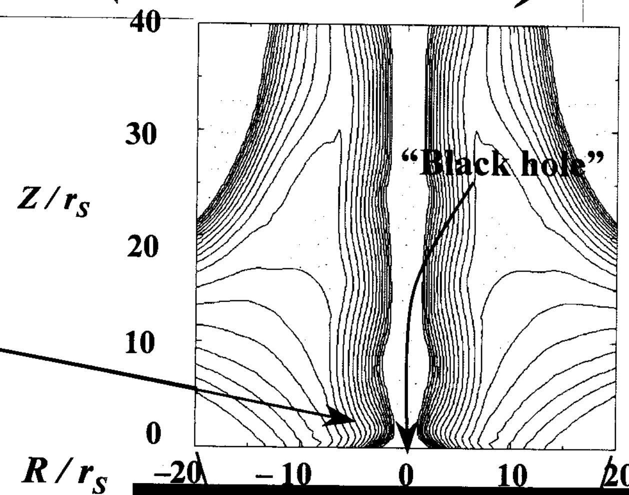
$$V \rightarrow U = \Gamma V$$

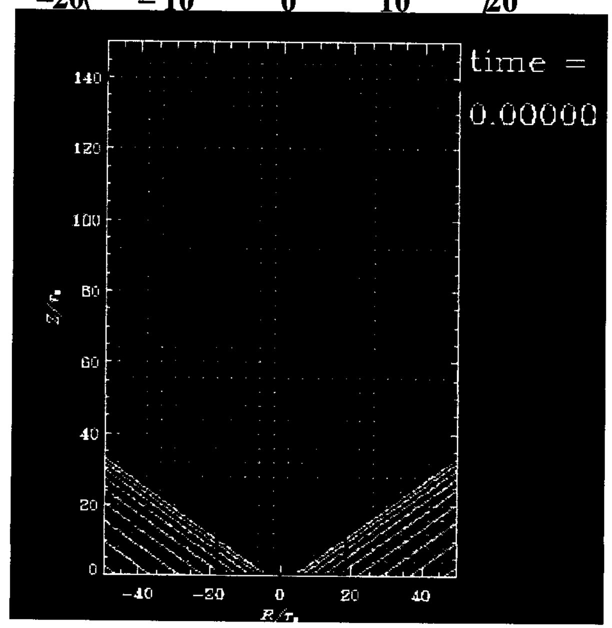
- In these simulations, velocities much greater than 1 can be identified with the Lorentz factor Γ
- Key ingredients in these pseudo-relativistic simulations (Lind, Meier, & Payne 1994; Meier *et al.* 1997; Meier *et al.* 2000):
  - Similar to previous "disk as boundary" simulations, but
  - Infinitely-thin accretion disk has an inner radius at $R=6GM/c^2$
  - B_R, B_φ, and V_R are all fixed on the boundary (as would be the case in an actual accretion disk)



Pseudo-Relativistic Simulations of Black Hole Accretion Disks (continued)

- Results (Meier et al. 1997; 2000):
  - This inner disk edge and fixed disk field create a new magnetic field structure:
    - Gravitational and magnetic forces cause injected corona to accrete inward, above the disk
    - This bends the magnetic field inward, creating a substantial B_R
    - Differential rotation winds B_R up into B_φ, which expels and collimates a narrow jet
  - This inner jet in the accreting corona case is similar to that in the accreting torus case shown by Shibata-san
  - A slowly-collimated disk wind (like the Blandford-Payne solutions) also occurs occasionally, but usually only when the inner jet is weak



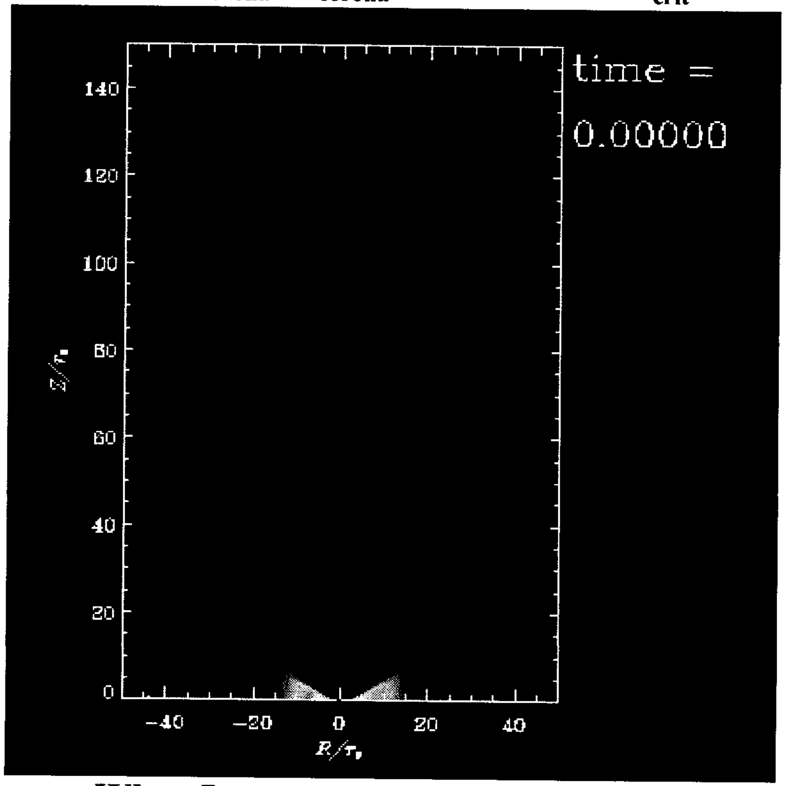


Pseudo-Relativistic Simulations of Black Hole Accretion Disks (continued)

- The "Magnetic Switch" process (Meier *et al.* 1997; Meier 1999):
  - There appears to be a critical MHD luminosity (analogous to the Eddington limit)

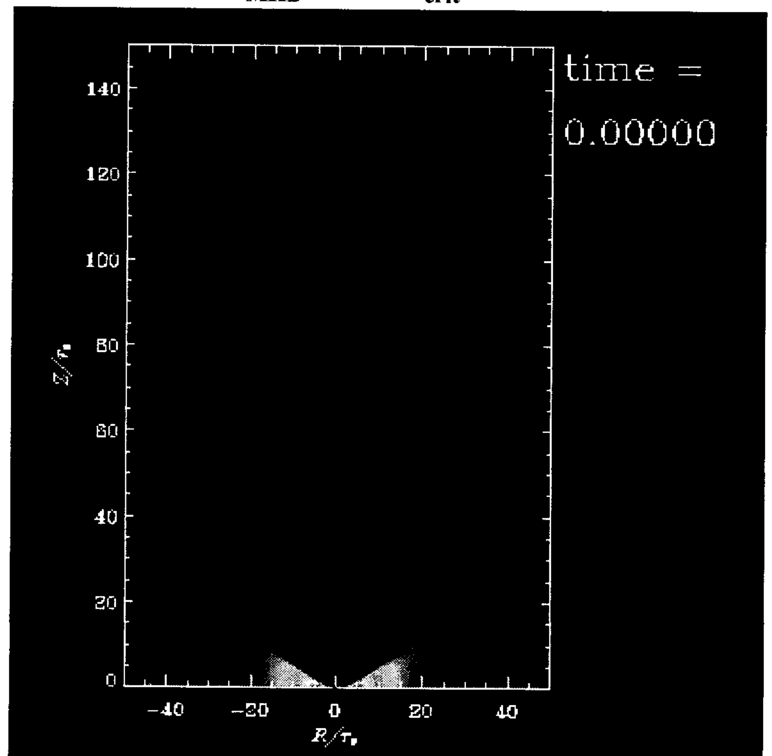
$$L_{crit} \equiv E_{escape}/\tau_{free\text{-}fall} = 4 \pi \rho_{corona} R_{corona}^2 (G M / R_{corona})^{3/2}$$

$L_{MHD} = B_{corona}^2 R_{corona}^4 \Omega^2 / 4c \sim 0.8 L_{crit}$



When $L_{MHD} < L_{crit}$, $V_{jet} \sim V_{esc}$, resulting in a relatively slow jet

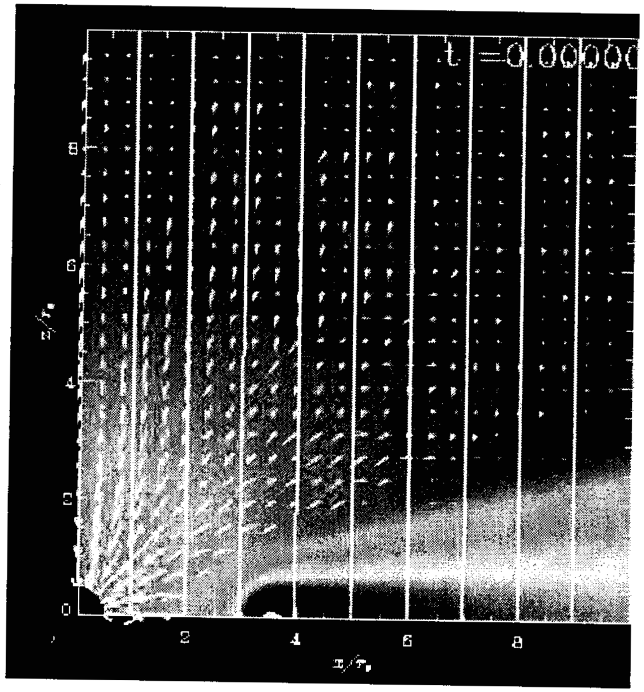
$L_{MHD} \sim 1.5 L_{crit}$



When $L_{MHD} > L_{crit}$, V_{jet} is determined by $L_{MHD} \sim \Gamma_{jet}$ [redacted] c^2, resulting in a relatively fast jet

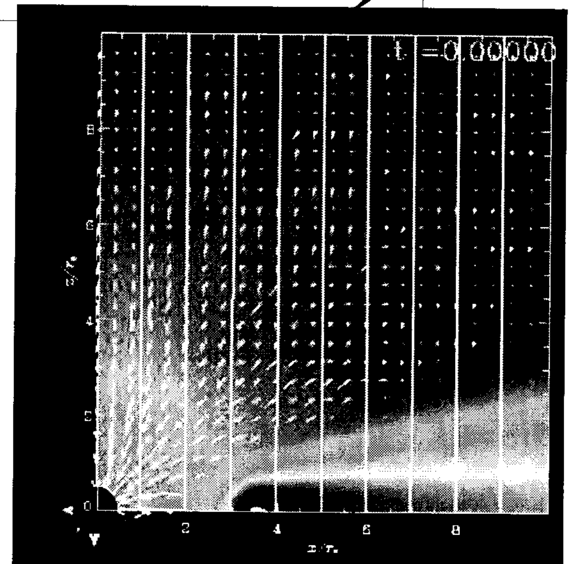
General Relativistic Simulations of Black Hole Accretion Disks

- Main papers: Koide, Shibata, & Kudoh (1998); Koide, Meier, Shibata, & Kudoh (1999a,b)
- Key ingredients:
  - Thick accretion disk with inner edge at R = 4.5 GM/c^2
  - Initial vertical weak magnetic field ($V_{Alfvén}$ = 0.01c)
  - Fixed general relativistic gravitational potential and fully relativistic MHD flow
- Five scenarios were simulated:
  - Non-rotating (Schwarzschild) black hole, non-rotating (ADAF-like) disk
  - Non-rotating black hole, Keplerian disk
  - Rotating (Kerr) black hole (*a/M*=0.95), non-rotating (ADAF-like) disk
  - Rotating black hole, Keplerian disk
    - Co-rotating with the black hole rotation
    - Counter-rotating against the black hole rotation

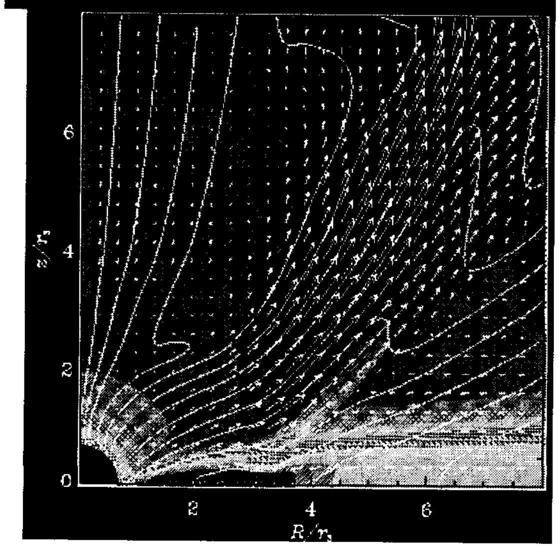


General Relati[redacted] Simulations of Black Hole Accretion Disks (continued)

- Results for Kerr (rotating) hole, counter-rotating disk:
  - Disk plunges rapidly toward black hole (counter-rotating orbits are unstable!)
  - Dragging of inertial frames by rotating black hole reverses spin of disk
  - A jet is generated from the inner disk edge in a manner similar to non-relativistic simulations
  - A very low density region forms inside the jet --- potentially the beginning of a magnetically-switched, high Lorentz factor flow



- Similar results for Kerr hole, non-rotating disk:
  - Disk free-falls rapidly into ergosphere
  - Rotation of black hole contributes significantly to acceleration of jet
  - Highest jet velocities achieved so far are of order the ergospheric escape velocity: $\Gamma < 3$



General Relativistic Simulations of Black Hole Accretion Disks (continued)

- Results for Kerr hole, co-rotating disk:
  - Disk accretes slowly toward black hole (co-rotating orbits are stable!)
  - Some outflow is produced, but it is rather slow so far ($V_{jet} \sim 0.4$ c)
  - Further evolution is unclear (simulation had to be stopped for numerical reasons)

- Results for Schwarzschild holes:
  - Jet is produced only when the disk is rotating
  - Jet speed is limited to $V_{jet} \sim V_{esc}$ ($R=6GM/c^2$) = 0.6 c

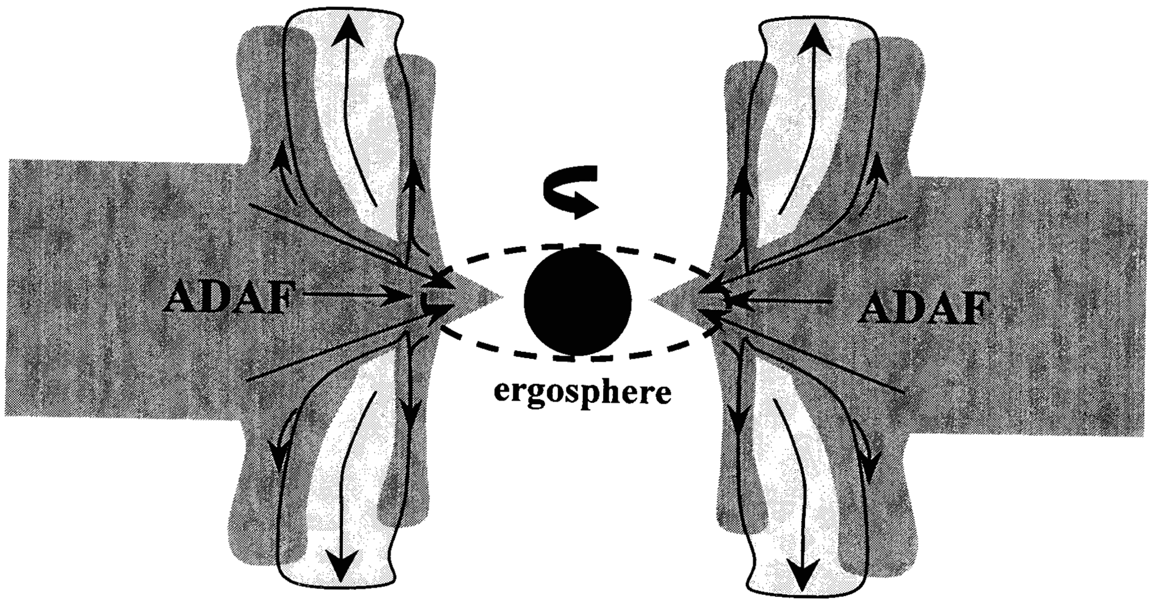
- Summary from all simulations: The fastest and most powerful jets are produced when
  - The central black hole rotates rapidly
  - The accreting material falls rapidly into the ergosphere
  - The material accelerated in the jet is of very low density
    (*i.e.*, $L_{MHD} > L_{crit}$ or, for Keplerian rotation, $V_{Alfvén} > V_{esc}$)

Summary of All Simulations Performed

- The fastest and most powerful jets are produced when
  - The central black hole rotates rapidly
  - The accreting material falls rapidly into the ergosphere
  - The material accelerated in the jet is of very low density ($i.e.$, $L_{MHD} > L_{crit}$ or, for Keplerian rotation, $V_{Alfvén} > V_{esc}$)

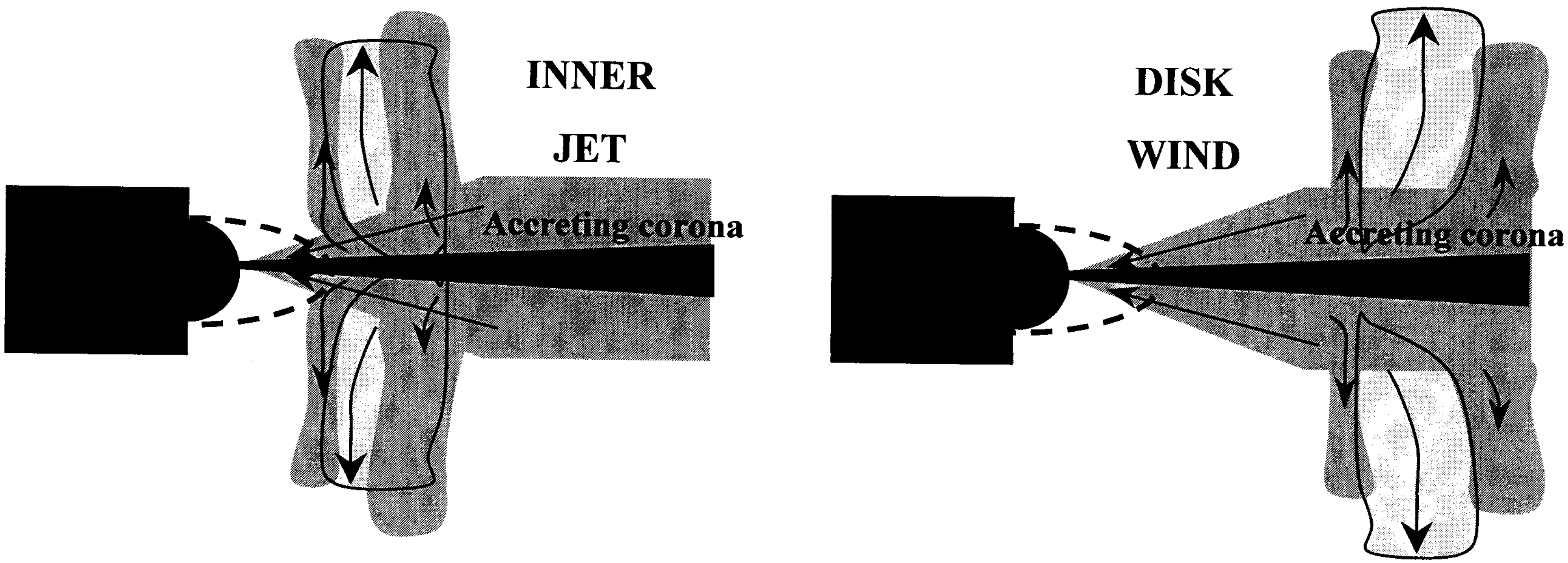
Two Possible Scenarios for AGN

- Scenario #1: Advection-Dominated Accretion Flow into Rotating Black Hole
  - Rapid infall toward black hole
  - Little rotation in the accretion flow until it plunges into the ergosphere
  - Jet is produced and collimated very near the black hole
  - Much of the outflow is at the escape velocity ($\Gamma < 3$)
  - Highest Lorentz-factor flow ($\Gamma >> 10$) can occur in low-density, Poynting-flux-dominated, "coronal holes"



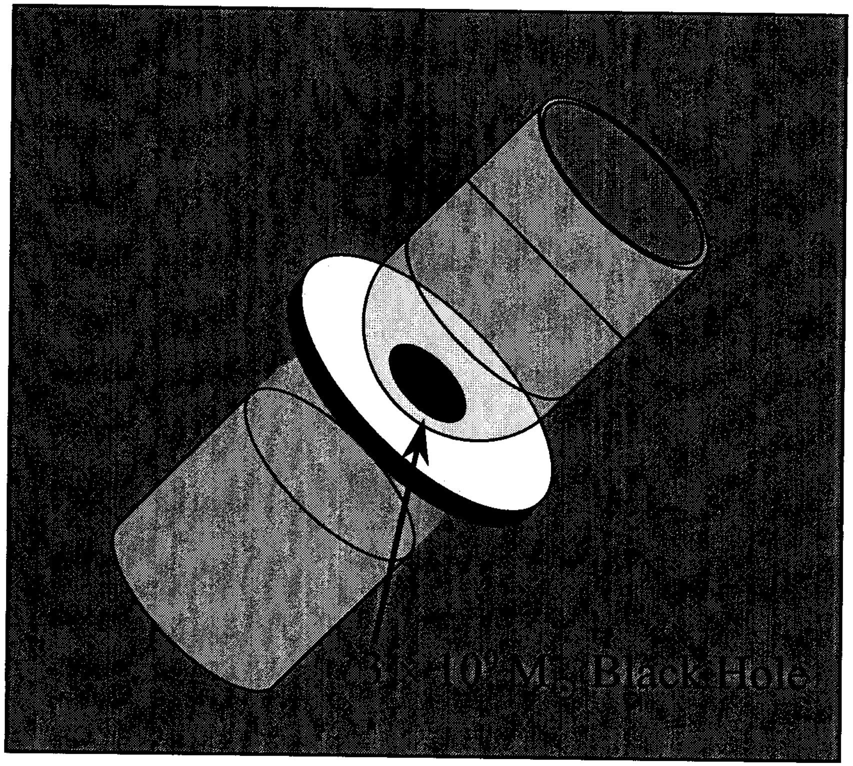
Two Possible Scenarios for AGN (continued)

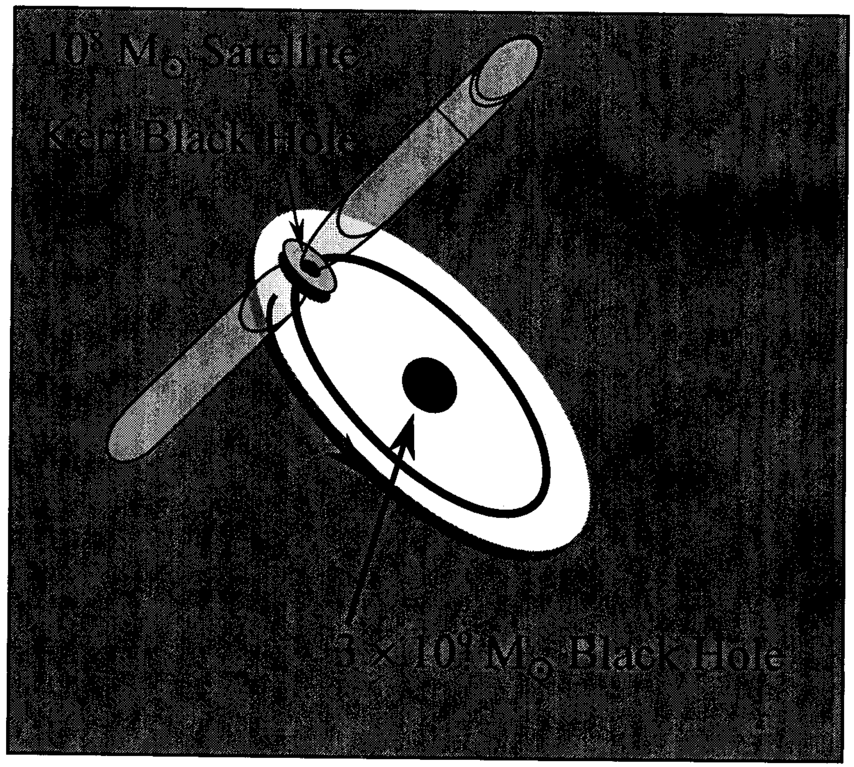
- Scenario #2: Advection-Dominated <u>Coronal</u> Accretion Flow
  - Magnetic field is anchored in thin Keplerian-rotating accretion disk
  - Rotating disk can accelerate inner jet <u>or</u> outer wind
  - Again, much of the outflow is at the escape velocity ($\Gamma < 3$)
  - But, high Lorentz-factor flow ($\Gamma >> 10$) can occur in low-density, Poynting-flux-dominated, "coronal holes"
  - <u>Jet can be collimated far from the black hole and still have a high Lorentz factor</u> (*cf.* M87)



Two Possible Models for M87: The Case for Space VLBI (Part II)

- Model #1: <u>broad relativistic wind</u> from accretion disk, collimating into a highly-relativistic jet
- Model #2: <u>satellite *rotating* black hole</u> with highly-collimated, relativistic inner jet





⇒ A SENSITIVE SPACE VLBI MISSION WITH 22 and 43 GHz IMAGING WILL BE ABLE TO DISTINGUISH BETWEEN THESE TWO MODELS

The Future

- General relativistic MHD simulations
  - Improve GRMHD code to handle very low-density flows
  - Investigate magnetic switching in fully-relativistic, finite-thickness accretion disk situations

- Accretion disk <u>structure</u> calculations
  - Investigate the structure of a rotating black hole magnetosphere and its implications for MHD-driven outflow